1-1-2008

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Keywords

ofdm, limitation, analysis, power, performance, peak, systems, idma

Disciplines

Engineering | Science and Technology Studies

Publication Details

J. Tong, Q. Guo & L. Ping, "Performance analysis of OFDM-IDMA systems with peak-power limitation," in IEEE International Symposium on Spread Spectrum Techniques and Applications, 2008, pp. 555-559.

Performance Analysis of OFDM-IDMA Systems with Peak-Power Limitation

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***Abstract*—This paper is concerned with orthogonal frequency-division multiplexing interleave-division multiple-access (OFDM-IDMA) systems over frequency-selective fading channels. Deliberate clipping is applied to reduce the peak-to-average power ratio (PAPR) of each user's transmitted signal. An iterative multiuser detection (MUD) technique is developed to recover the performance loss due to clipping. A semi-analytical signal-to-noise ratio (SNR) evolution technique is proposed, which can provide quick and accurate prediction of the iterative MUD performance. Numerical results show that the performance of OFDM-IDMA is not sensitive to the frequency selectivity of channels, and OFDM-IDMA is more power-efficient than other alternative multi-carrier transmission techniques.**

I. Introduction

It has been shown recently that the advantages of orthogonal frequency-division multiplexing (OFDM) and interleave-division multiple-access (IDMA) [1], [2], [3] can be combined in an OFDM-IDMA scheme [4], [5], in which OFDM operations are adopted to resolve the inter-symbol interference (ISI) induced by multi-path channels, and the signals of different users are distinguished by user-specific interleavers based on the IDMA principle. The multiple-access interference (MAI) can be suppressed by very low-cost IDMA-type multiuser detection (MUD). OFDM-IDMA [4], [5] is a promising approach for resolving the two main obstacles in wireless communications, namely, the ISI and the MAI.

Similar to other multi-carrier systems, OFDM-IDMA suffers a peak-to-average power ratio (PAPR) problem. The transmitted signal of OFDM-IDMA has a high PAPR, which may degrade the efficiency of power amplifiers of the transmitters.

In this paper, we apply the deliberate clipping technique [6], [7], [8] to alleviate the PAPR problem of OFDM-IDMA. An iterative MUD method is developed to jointly treat the MAI and clipping effect for clipped OFDM-IDMA. The system performance is analyzed. A signal-to-noise (SNR) evolution technique is applied to predict the bit-error-rate (BER) performance. Numerical examples demonstrate that (i) the PAPR can be significantly reduced with moderate BER increase; (ii) OFDM-IDMA is not sensitive to the frequency selectiveness of channels provided that sufficient spreading is used; and (iii) OFDM-IDMA can achieve a significant improvement in power efficiency when compared with other alternative multi-carrier multiuser schemes.

II. Transmitter Principles

The transmitter/receiver structure of an OFDM-IDMA system with K active users is shown in Fig. 1. At the transmitter for user-k, the information data is forward-error-correction (FEC)-encoded into a sequence $c_k = \{c_k[m]\}$. Each coded bit $c_k[m] \in \{+1, 1\}$ is spread using a length-S repetition code, interleaved by a user-specific interleaver, and then mapped to a complex sequence $x_k = \{x_k[n]\}$ by using quadrature-phase-shift-keying (QPSK). Each dimension of $x_k[n]$ (denoted by $x_k^{\mathrm{Re}}[n]$ or $x_k^{\mathrm{Im}}[n]$) represents a replica of a bit in c_k. The sequence x_k is then modulated onto sub-carriers by using an $N-$point inverse discrete Fourier transform (IDFT).

Due to the IDFT operation, the time-domain signal is a weighted sum of N QPSK symbols, which has a high PAPR. Clipping with oversamping is a straightforward and efficient approach to reduce PAPR [6]. The transmitted signal is oversampled into $\{X_k[i]\}$ and then clipped as follows:

$$\mathrm{clp}(X_k[i]) = \begin{cases} X_k[i], & |X_k[i]| < A \\ AX_k[i]/|X_k[i]|, & |X_k[i]| \geq A \end{cases} \tag{1}$$

where $A > 0$ is the clipping threshold. Then, $\{\mathrm{clp}(X_k[i])\}$ is band-pass filtered and transmitted.

The clipping ratio (in decibel) is defined as $\mathrm{CR} = 10\log_{10}(A^2/\mathrm{E}[|X_k[i]|^2])$, where $\mathrm{E}[\cdot]$ denotes the mathematical expectation. To simplify the derivations below, we assume that Nyquist-rate sampled clipping is used (i.e., the oversampling factor is one) and the clipping ratio is the same for all users, but the extensions to more general cases are straightforward. Note that the clipping operation in (1) is nonlinear. Following [8], we can model (1) by a linear process as

$$\mathrm{clp}(X_k[i]) = \alpha X_k[i] + \mathrm{clpn}(X_k[i]). \tag{2}$$

Here, α is a constant given by $\alpha = \mathrm{E}[X_k^*[i]\mathrm{clp}(X_k[i])]/\mathrm{E}[|X_k[i]|^2]$ where * denotes complex conjugate, and $\mathrm{clpn}(X_k[i]) \equiv \mathrm{clp}(X_k[i]) - \alpha X_k[i]$ is the clipping noise that is statistically uncorrelated with $X_k[i]$.

III. Receiver Principles

A. Preliminaries

To facilitate the discussions below, we denote the frequency- and time-domain transmit signal vectors by $\mathbf{x}_k =$

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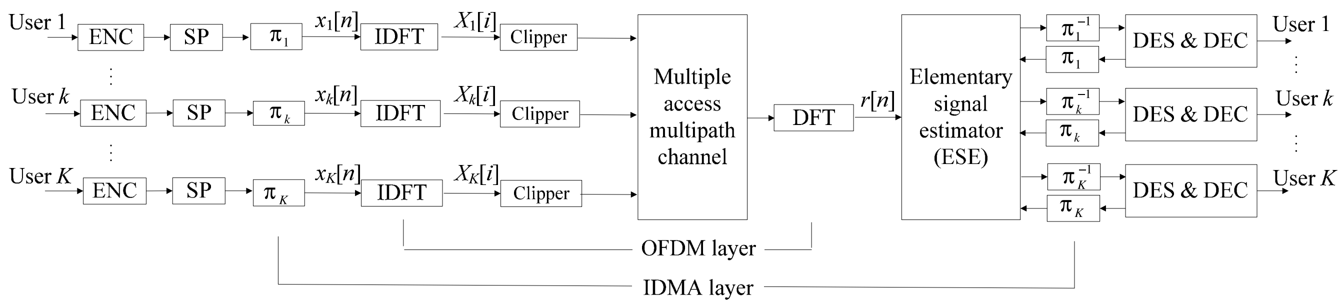

Fig. 1. Transmitter/receiver structure for OFDM-IDMA. Cyclic prefix insertion and removal for OFDM modulation are not shown for simplicity. ENC, SP, DEC and DES denote encoder, spreader, decoder and de-spreader, respectively.

$[x_k[0], \cdots, x_k[N-1]]^T$ and $\mathbf{X}_k = [X_k[0], \cdots, X_k[N-1]]^T$, respectively. From Section II, we have

$$\mathbf{x}_k = \mathbf{F}\mathbf{X}_k, \quad \mathbf{X}_k = \mathbf{F}^H \mathbf{x}_k \tag{3}$$

where $\mathbf{F}$ denotes the $N \times N$ unitary discrete Fourier transform (DFT) matrix and $(\cdot)^H$ denotes the conjugate transpose. The clipped time-domain signal vector is defined by

$$\mathrm{clp}(\mathbf{X}_k) = [\mathrm{clp}(X_k[0]), \cdots, \mathrm{clp}(X_k[N-1])]^T$$

and the clipping noise vector is denoted by

$$\mathrm{clpn}(\mathbf{X}_k) = \mathrm{clp}(\mathbf{X}_k) - \alpha \mathbf{X}_k. \tag{4}$$

For a complex random variable x with real part x^{Re} and imaginary part x^{Im}, we define its mean and variance as

$$\mathrm{E}[x] = \mathrm{E}[x^{\mathrm{Re}}] + j\mathrm{E}[x^{\mathrm{Im}}] \tag{5}$$

and

$$\mathrm{Var}[x] = \mathrm{E}[|x|^2] - |\mathrm{E}[x]|^2, \tag{6}$$

respectively, where $j = \sqrt{-1}$.

B. Iterative Detection

As shown in Fig. 1, the core of the OFDM-IDMA receiver consists of an elementary signal estimator (ESE) and K *a posteriori* probability decoders (APP DECs). Since the APP decoding is a standard function, we focus on the ESE.

After the OFDM demodulation, the frequency-domain received signal can be represented as

$$r[n] = \alpha \sum_{k=1}^{K} h_k[n] x_k[n] + \sum_{k=1}^{K} h_k[n] d_k[n] + z[n], \tag{7}$$

where $\{z[n]\}$ are samples of a complex additive white Gaussian noise (AWGN) with mean zero and variance σ^2, and $d_k[n]$ represents the clipping noise from user k. From (4),

$$\mathbf{d}_k \equiv [d_k[0], \cdots, d_k[N-1]]^T = \mathbf{F}\mathrm{clpn}(\mathbf{X}_k). \tag{8}$$

The channel coefficient $h_k[n]$ related to the nth sub-carrier for user k is the DFT of the L channel taps $\{H_k[l], l = 0, 1, \cdots, L-1\}$ seen by user k, i.e.,

$$h_k[n] = \sum_{l=0}^{L-1} H_k[l] e^{-j2\pi nl/N}.$$

The conventional MUD technique in [1] can be applied to detect $x_k[n]$ if there is no clipping (i.e., $\alpha = 1, d_k[n] = 0, \forall k, \forall n$). When the clipping effect is present, the conventional MUD can also be applied by treating $d_k[n]$ as an AWGN, following [7]. However, the performance may degrade significantly in this way, as shown in Fig. 3 below. Here, we propose a modified MUD method to improve performance.

To estimate $x_k[n]$, we can rewrite (7) as

$$r[n] = \alpha h_k[n] x_k[n] + \xi_k[n] \tag{9}$$

where

$$\xi_k[n] = \alpha \sum_{m=1, m\neq k}^{K} h_m[n] x_m[n] + \sum_{m=1}^{K} h_m[n] d_m[n] + z[n] \tag{10}$$

represents the interference-plus-noise component in $r[n]$ with respect to $x_k[n]$. From the central limit theorem, $\xi_k[n]$ can be approximated by a Gaussian random variable. Note that the mean $\mathrm{E}[x_m[n]]$ and variance $\mathrm{Var}[x_m[n]]$ can be estimated from the DEC feedbacks, as in [1], [3]. If $\mathrm{E}[d_m[n]]$ and $\mathrm{Var}[d_m[n]]$ are also available, then the following iterative detection/decoding procedure can be applied.

(i) The ESE computes $\mathrm{E}[\xi_k[n]]$ and $\mathrm{Var}[\xi_k[n]]$ based on (10).

(ii) The ESE computes the *extrinsic* log-likelihood ratio (LLR) about $x_k^{\mathrm{Re}}[n]$, defined by

$$e_{\mathrm{ESE}}(x_k^{\mathrm{Re}}[n]) = \ln\left(\frac{\Pr(r[n]|x_k^{\mathrm{Re}}[n] = +1)}{\Pr(r[n]|x_k^{\mathrm{Re}}[n] = -1)}\right). \tag{11}$$

Let $\alpha h_k[n] = |\alpha h_k[n]| e^{j\theta_k[n]}$, then (11) can be computed based on (9) as

$$e_{\mathrm{ESE}}(x_k^{\mathrm{Re}}[n]) = 4\frac{|\alpha h_k[n]|}{\mathrm{Var}[\xi_k[n]]} \mathrm{Re}(e^{-j\theta_k[n]}(r[n] - \mathrm{E}[\xi_k[n]])). \tag{12}$$

In a similar way, we can obtain $e_{\mathrm{ESE}}(x_k^{\mathrm{Im}}[n])$.

(iii) The results from step (ii) are delivered to the APP despreaders (DES's). Let $\mathcal{I}_m$ be the position index set of the S replicas of $c_k[m]$ after interleaving. We assume that these replicas are all transmitted in the real part of $x_k[n]$. (Note: This restriction is only to simplify the notations below.) The output of the DES for user k is then the LLR summation involving only the real part of $x_k[n]$ (noting that $x_k^{\rm Re}[n] = c[m]$ for all $n \in \mathcal{I}_m$)

$$e_{\rm DES}\left(c_k[m]\right) = \sum_{n\in\mathcal{I}_m} e_{\rm ESE}(x_k^{\rm Re}[n]). \tag{13}$$

The details of this step can be found in [1].

(iv) Taking the DES outputs as inputs, the DECs perform the APP decoding. The outputs of DECs are then used to refine means and variances of $x_k[n]$ and $d_k[n]$.

Now, the key is to find $\mathrm{E}[d_k[n]]$ and $\mathrm{Var}[d_k[n]]$.

C. Clipping Noise Estimation

Recalling (8), we can find the statistics of $d_k[n]$ from those of $\{\mathrm{clpn}(X_k[i])\}$. From (3), each entry X of $\mathbf{X}$ is a weighted sum of N random variables. When N is large, we can model X as a circularly symmetric, complex Gaussian random variable, i.e., $X \sim \mathcal{CN}(\mathrm{E}[X], \mathrm{Var}[X])$. The mean $\mathrm{E}[X]$ and variance $\mathrm{Var}[X]$ can be estimated from $\{\mathrm{E}[x_k[n]], \mathrm{Var}[x_k[n]]\}$ as shown below. Then the statistics of the clipping noise $\mathrm{clpn}(X)$ can be computed as

$$\begin{aligned}\mathrm{E}[\mathrm{clpn}(X)] &= \int_{|X|\geq 0} \mathrm{clpn}(X)p(X)dX\\ \mathrm{Var}[\mathrm{clpn}(X)] &= \int_{|X|\geq 0} |\mathrm{clpn}(X)|^2 p(X)dX - |\mathrm{E}[\mathrm{clpn}(X)]|^2\end{aligned} \tag{14}$$

where $p(X) = e^{-|X-\mathrm{E}[X]|^2/\mathrm{Var}[X]}/(\pi\mathrm{Var}[X])$. Note that (14) can be evaluated by the look-up table method introduced in [9].

Based on the above discussions, the mean and variance of $d_k[n]$ can be found as follows.

(i) Generate the means and variances of the entries of $\mathbf{X}_k$ based on the relationship in (3). More specifically, $\mathrm{E}[\mathbf{X}_k] = \mathbf{F}^H\mathrm{E}[\mathbf{x}_k]$, where $\mathrm{E}[\mathbf{x}_k]$ and $\mathrm{E}[\mathbf{X}_k]$ are, respectively, the means of $\mathbf{x}_k$ and $\mathbf{X}_k$. The variance of $X_k[i]$ is computed as $\mathrm{Var}[X_k[i]] = 1/N\sum_{n=0}^{N-1}\mathrm{Var}[x_k[n]]$.

(ii) Generate the mean and variance of the time-domain clipping noise using (14).

(iii) Generate the mean and variance of the frequency-domain clipping noise $d_k[n]$ based on the relationship in (8) (using a procedure similar to Step (i) above).

The results of the above procedure are used to update $\mathrm{E}[\xi_k[n]]$ and $\mathrm{Var}[\xi_k[n]]$ in the ESE.

IV. Performance Analysis

A. Performance Prediction

Consider a frequency-selective fading channel model in (7). We assume that $\{h_k[n], \forall k, \forall n\}$ are mutually independent. From the above discussions, user-k's signal is detected by treating $\xi_k[n]$ in (9) as a Gaussian noise with mean $\mathrm{E}[\xi_k[n]]$. Note that $\xi_k[n] - \mathrm{E}[\xi_k[n]]$ is a summation of $2K$ random variables. When K is large, by the central limit theorem, we can approximately model $\xi_k[n] - \mathrm{E}[\xi_k[n]]$ as a sample of a circularly symmetric complex AWGN with zero mean and average power

$$\begin{aligned}I_k &\equiv \mathrm{E}[|\xi_k[n] - \mathrm{E}[\xi_k[n]]|^2] = \mathrm{E}[\mathrm{Var}[\xi_k[n]]]\\ &= |\alpha|^2\sum_{m=1,m\neq k}^{K}\eta_m v_{x,m} + \sum_{m=1}^{K}\eta_m v_{d,m} + \sigma^2,\end{aligned} \tag{15}$$

where

$$\eta_m \equiv \mathrm{E}[|h_m[n]|^2], v_{x,m} \equiv \mathrm{E}[\mathrm{Var}[x_m[n]]], v_{d,m} \equiv \mathrm{E}[\mathrm{Var}[d_m[n]]]$$

denote user-m's average channel power gain, the average MAI power and clipping noise power due to user-m, respectively. In this way, we can make the following assumption:

$$\mathrm{Var}[\xi_k[n]] \approx I_k, n = 0, 1, \cdots, N-1. \tag{16}$$

Now, from (12) and (9), we have

$$\begin{aligned}&e_{\rm ESE}(x_k^{\rm Re}[n]) + je_{\rm ESE}(x_k^{\rm Im}[n])\\ &\approx \frac{4\,|\alpha h_k[n]|}{I_k}(|\alpha h_k[n]|x_k[n] + e^{-j\theta_k[n]}(\xi_k[n] - \mathrm{E}[\xi_k[n]])).\end{aligned} \tag{17}$$

Then, the performance of the ESE can be approximately characterized by the SNR with respect to $x_k[n]$ in (17), i.e.,

$$\mathrm{snr}_k \equiv \frac{\mathrm{E}[|\alpha h_k[n]x_k[n]|^2]}{\mathrm{E}[|\xi_k[n] - \mathrm{E}[\xi_k[n]]|^2]} = \frac{2|\alpha|^2\eta_k}{I_k} \tag{18}$$

where we have assumed $\mathrm{E}[|x_k[n]|^2] = 2$. In other word, the ESE performance approaches that of a single-user spread system over a frequency-selective channel with SNR given by (18).

A useful consequence of the above discussion is that the SNR evolution technique for plain IDMA over quasi-static flat fading channels [1] can be borrowed to predict the performance of OFDM-IDMA in frequency selective fading channels, which provides a very efficient tool for performance analysis and optimization in OFDM-IDMA[1]. This strategy is demonstrated by the numerical examples in Section V.

B. Effect of Spreading

We next investigate the impact of spreading on system performance. Following (17), the DES output generated by (13) can be approximated as

$$e_{\rm DES}\left(c_k[m]\right) \approx \frac{4}{I_k}\left(\gamma_k[m]c_k[m] + \beta_k[m]\right) \tag{19}$$

where

$$\gamma_k[m] = \sum_{n\in\mathcal{I}_m}|\alpha h_k[n]|^2$$

and

$$\beta_k[m] = \sum_{n\in\mathcal{I}_m}|\alpha h_k[n]|\left(\mathrm{Re}(e^{-j\theta_k[n]}(\xi_k[n] - \mathrm{E}[\xi_k[n]]))\right).$$

[1]The SNR evolution method based on (18) may underestimate the real system performance due to the approximation in (16).

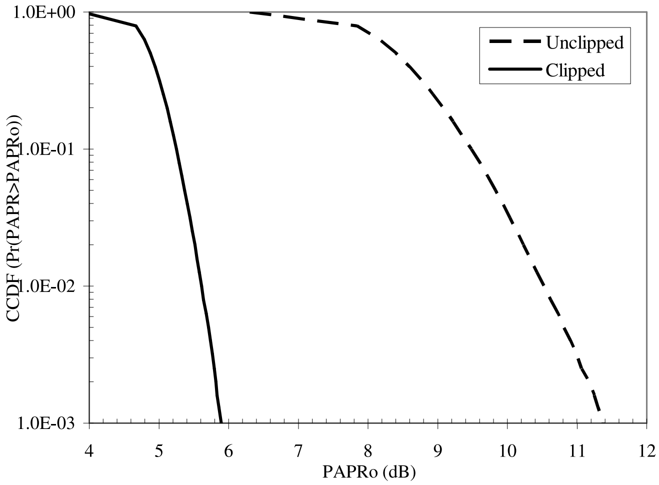

Fig. 2. CCDF of the PAPR of OFDM-IDMA systems with and without clipping.

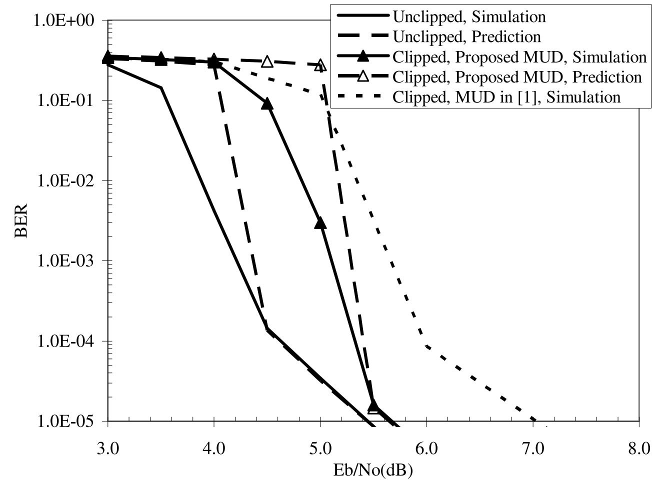

Fig. 3. Performance of OFDM-IDMA with and without clipping. Each user employs rate-$1/2$ convolutional code with generator $(23, 35)_8$. The spreading length is $S = 8$. The number of users is 16 and the system throughput is 2 bits per channel use. The information block length for each user is 512. The clipping parameters are the same as those in Fig. 2. The number of iterations is 10.

Following Section IV-A, we approximate $\beta_k[m]$ by a Gaussian random variable with $\mathrm{E}[\beta_k[m]] = 0$ and $\mathrm{Var}[\beta_k[m]] \approx |\alpha|^2 \sum_{n\in\mathcal{I}_m} |h_k[n]|^2 I_k/2$. Thus, the SNR in the DES outputs can be approximated as

$$\mathrm{snr}_{\mathrm{DES}}[m] = \frac{|\gamma_k[m]|^2}{\mathrm{Var}[\beta_k[m]]} \tag{20}$$

$$\approx \frac{\left(\sum\limits_{n\in\mathcal{I}_m} |\alpha h_k[n]|^2\right)^2}{\sum\limits_{n\in\mathcal{I}_m} |\alpha h_k[n]|^2 I_k/2} = \frac{2|\alpha|^2 \sum\limits_{n\in\mathcal{I}_m} |h_k[n]|^2}{I_k}. \tag{21}$$

Note that the BER performance is determined by SNR of the DES outputs (i.e., the DEC inputs). When S is sufficiently large, $\sum_{n\in\mathcal{I}_m} |h_k[n]|^2 \to S\mathrm{E}[|h_k[n]|^2] = S\eta_k$. Thus, for large S, the BER performance of OFDM-IDMA over frequency-selective channels approaches that over AWGN channels.

V. Numerical Results

Sections II-IV assume Nyquist-rate sampled clipping. In practice, clipping with oversampling can reduce the PAPR more effectively. The discussions above can be readily extended to the oversampled cases. In the following, we assume that the number of sub-carriers $N = 256$, the oversampling factor is 4 and $\mathrm{CR} = 0$ dB. For simplicity, the overhead due to cyclic prefixing is ignored below. The PAPR of the transmitted signal can be investigated using the methodology in [7]. The complementary cumulative distribution function (CCDF) of the PAPR is shown in Fig. 2. It is seen that the PAPR is less than 5.9 dB for 99.9% of the OFDM blocks with clipping, in contrast to 11.3 dB in the unclipped case.

A. Efficiency of the Proposed MUD

We first examine the efficiency of the proposed MUD technique. We consider a fully-interleaved Rayleigh fading channel model as in [11], where $h_k[n]$ are independent, identically complex-Gaussian distributed with mean 0 and variance 1. Fig. 3 shows the performance of a 16-user OFDM-IDMA system. (The parameters are listed in the caption.) We can make the following observations.

- The proposed MUD technique outperforms the conventional MUD in [1] when clipping is used.
- Clipping degrades the BER performance. However, at $\mathrm{BER} = 10^{-5}$, the performance loss is marginal.
- The performance predicted by the SNR evolution technique is close to the simulated performance.

B. Effect of Spreading

Fig. 4 shows the performance of an OFDM-IDMA system for a range of spreading lengths S over frequency-selective fading channels and the AWGN channels. The transmission scheme and the frequency-selective channel model are the same as those in Fig. 3. The spreading length $S = 2, 4, 16$ and the number of users $K = 2S$, so that the system throughput is kept constant ($R = 2$ bits per channel use). We can see from Fig. 4 that, when the spreading length $S \geq 4$, the performance of OFDM-IDMA are very close in both types of channels. This implies that the OFDM-IDMA performance is not sensitive to the frequency-selectivity of the channels, as discussed in Section IV-B.

C. Performance Optimization

Finally, we show that the performance of OFDM-IDMA can be optimized using the power allocation technique developed in [1]. The basic system parameters are the same as those for Fig. 3 except for the following changes. We consider the system throughput of 3 bits per channel use with $S = 8$ and 24 users. In addition to the Rayleigh fading factor used in Fig. 3, we also consider path loss and shadow fading. For path loss, we assume that the users are uniformly distributed in a single hexagonal cell and the distance from the farthest corner of the cell to the base station is normalized to 1. The fourth power

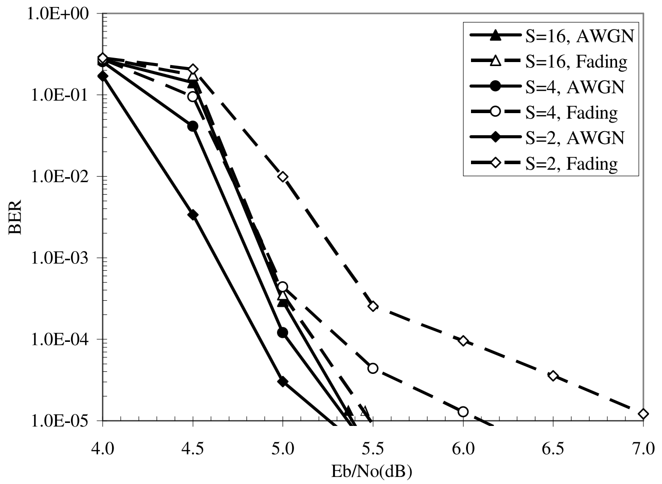

Fig. 4. Performance comparison of clipped OFDM-IDMA over AWGN and frequency-selective fading channels when different spreading lengths are used. The information block lengths are 4096, 2048, and 512, respectively for $S = 2, 4$ and 16. The number of iterations is 10. The system throughput is 2 bits per channel use. The clipping parameters are the same as those in Fig. 2.

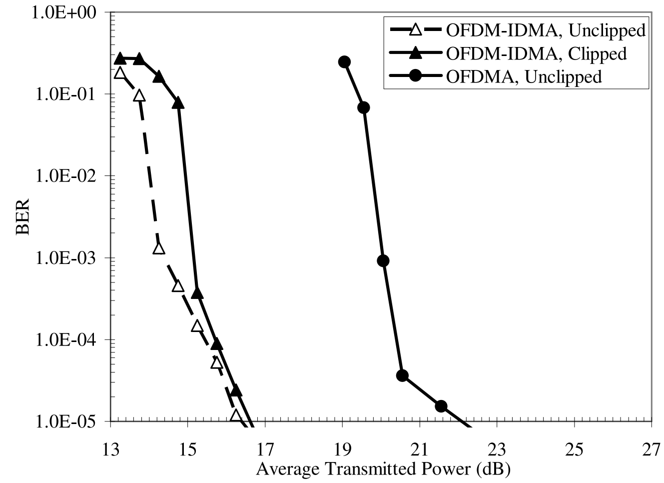

Fig. 5. Comparison of the power efficiency of OFDM-IDMA and OFDMA in an uplink scenario. The system throughput is $R = 3$ bits per channel use. The number of iterations is 10. The clipping parameters are the same as those in Fig. 2. The lognormal fading is scaled such that its mean equals 1. The power of the channel noise is normalized to 1 (i.e., 0 dB).

TABLE I
POWER LEVELS OF THE OFDM-IDMA SYSTEMS IN FIG. 5.

User Number	13	2	2	7
Power Level (dB)	0	3.1677	3.9596	5.5430

law is used. For shadow fading, a lognormal random variable with standard deviation 8 dB is used.

Assume that the transmitters only have knowledge of the path loss and shadow fading factors. The Rayleigh fading coefficients are not known at the transmitters. We allow an outage probability of 1%. The power allocation and channel matching technique in [1] is used. The optimized received power profile for the 24 users are given in Table I. Fig. 5 shows the BER of the OFDM-IDMA system versus the average total transmitted power. For comparison, we also give the performance of an OFDMA system with the same throughput based on the iteratively decoded BICM scheme using 16-QAM and modified set partitioning mapping [12]. It can be observed from Fig. 5 that OFDM-IDMA significantly outperforms OFDMA. This is attributed to the so-called multi-user gain of a non-orthogonal scheme over an orthogonal one [13], [14]. Clearly, OFDM-IDMA provides an effective means to realize multi-user gain over frequency-selective channels.

VI. CONCLUSIONS

Recall that CDMA is not sensitive to the frequency selectiveness of channels when rake receivers are used [10]. In this paper we establish a similar conclusion for deliberately clipped OFDM-IDMA systems. Consequently, we can borrow many existing techniques for IDMA developed for flat fading channels. In particular, significant performance improvement can be achieved using an unequal power allocation technique, as demonstrated by numerical examples.

ACKNOWLEDGMENT

This work was supported by a grant from the Research Grant Council of the Hong Kong, under Project CityU 116706.

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